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Report

The Induced Forces and Motions of a Tumblehome Hullform (Model 5613) Undergoing Forced Roll

by

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Predictions of large amplitude roll motions and capsize events have proven to be difficult and include large uncertainty. One of the reasons for this is a lack of knowledge of resultant forces and moments for large roll angles. Currently, the equations used by numerical models to predict forces and moments due to roll motion are based on experimental data performed within a small range of roll amplitudes. A data set of forces and moments is necessary to verify that the model predictions are accurate in the upper ranges, or to develop new models to predict the forces and moments for these larger roll amplitudes.

In 2005, the Naval Surface Warfare Center, Carderock Division, tested NSWC Model 5613, a tumblehome hullform, with the primary objective of obtaining model scale constrained seakeeping results to provide information necessary to perform verification of surge, sway, heave forces and motions, and roll, pitch, and yaw moments and motions acting on a surface combatant hull during large amplitude motions and capsize events. This report describes the testing and the resultant acquired data and begins to establish a database defining non-linear forces and moments associated with large amplitude motions and capsize events.

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Abstract

Predictions of large amplitude roll motions and capsize events have proven to be difficult and include large uncertainty. One of the reasons for this is a lack of knowledge of resultant forces and moments for large roll angles. Currently, the equations used by numerical models to predict forces and moments due to roll motion are based on experimental data performed within a small range of roll amplitudes. A data set of forces and moments is necessary to verify that the model predictions are accurate in the upper ranges, or to develop new models to predict the forces and moments for these larger roll amplitudes.

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Administrative Information

The work described in this report was performed by the Control and Maneuvering (Code 5600) and Resistance and Powering (Code 5200) Divisions of the Hydromechanics Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). This work was funded by the Office of Naval Research, contract number N0001405WX20612. Dr. L. Patrick Purtell is the program manager.

Acknowledgements

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Introduction

Various numerical methods are available to predict ship motions. Ikeda (1) developed a component-based method for the prediction of ship roll damping about 25 years ago, which is still currently used. This method is based on both theory and empirical data. Matusiak (2) has developed a two-stage approach to the determination of large amplitude motions of a rigid ship in waves, which qualitatively agreed with experimental results. Gorski (3) discusses the role of Reynolds Averaged Navier-Stokes (RANS)

Figure 1. Rendered profile of Model 5613.

equations in solving seakeeping problems, where he describes an accurate RANS prediction of the roll motion (15 degrees) of a cylinder with forward speed.

Experimental work is also currently being performed to further the effort of understanding large amplitude ship motions. Experiments to study extreme ship motions have been performed at INSEAN (the Italian ship model basin) for surface combatant hulls free to heave and roll in beam seas (4). Irvine (5) performed a range of free roll decay experiments at the University of Iowa for a surface combatant hull, where motions, forces, and moments were measured.

The ability to predict the forces and moments experienced by a ship hull undergoing large amplitude motions is important. Predictions of such motions have been based on physical model experiments and numerical models, which use empirical equations based on experimental data performed within a small range of roll amplitudes. A data set of forces and moments due to a larger range of roll amplitudes is necessary to verify that the methods used in model predictions are accurate in the upper ranges, or to develop new methods to predict the forces and moments for these larger roll amplitudes.

The objective of this experiment is to obtain the model scale constrained seakeeping results to provide information necessary for numerical model verification of surge, sway, and heave forces and roll, pitch, and yaw moments acting on a surface combatant hull during large amplitude motions and capsize events. Effects of model speed, roll amplitude, and roll frequency on the forces and moments are investigated.

A modern surface combatant model (λ= 32, Model 5613) with 10 degree tumblehome sides was tested on Carriage 2 at NSWCCD and forced in roll using a motor-driven mechanism. The mechanism was used to drive the model through large roll amplitudes of up to 50 degrees to port and starboard while also varying the roll frequency.

Model Description

The model used for this test was the 1/32 scale NSWCCD Model 5613. This model had 10 degree tumblehome sides. A rendered profile of Model 5613 is shown in Figure 1, and the body plan is shown in Figure 2. A summary of the hull design characteristics for the model are shown in Table 1. Due to the weight of the roll-forcing mechanism, the tested draft was 2.54 cm (1 in) greater than the design draft. The model was fitted with bilge keels of 1.25 m span (full scale), that were centered at midship, with a chord length equal to 1/3 the ship length. No other appendages were included in this test.

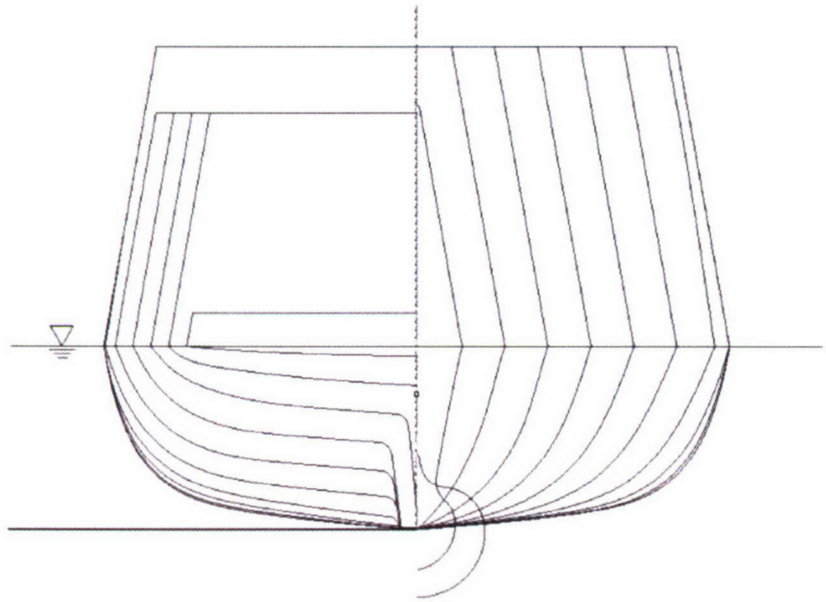


Figure 2. Body plan of Model 5613.

Table 1. Model 5613 Hull Design Characteristics

	1/32 Model-Scale 20C, FW	
Lpp	4.81 m	15.8 ft
Beam	58.8 cm	1.93 ft
L/B	8.2	8.2
Max. Depth	45.3 cm	1.49 ft
Max. Freeboard	28.1 cm	0.92 ft
Draft	17.2 cm	0.56 ft
Displacement	261 kg	575 lbs
LCB (aft of FP)	2.49 m	8.16 ft
VCB (above BL)	10.2 cm	0.33 ft
KM_T	30.4 cm	1.00 ft

The radii of gyration and the vertical center of gravity (VCG) of the hull were determined by inclining and swinging the underbody from NSWCCD's inertia A-frame apparatus. The VCG was determined to be 24.1 cm (9.5 inches) above the keel, with a pitch gyradius of 100.3 cm (39.5 inches), roll gyradius of 21 cm (8.25 inches), and a yaw gyradius of 100.6 (39.62 inches). The longitudinal center of gravity (LCG) was determined to be 10.9 cm (4.3 inches) aft of midship. The roll motion was forced at 24.1 cm (9.5 inches) above the keel, and 8.1 cm (3.2 inches) aft of midship.

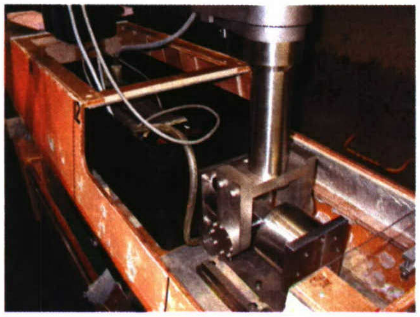
Two components of data in this experiment will be affected by the 0.03 m (1.1 inch) difference between LCG and the center of rotation, the pitch motion and the yaw moment. In the data presented later in this report, the yaw moment is shown "as collected", as well as corrected for the difference between the LCG and the longitudinal center of rotation for the mechanism. The measured pitch motion will be the same along the centerline of the model, although the actual pitch motion would be slightly different as a result of the 0.03 m (1.1 inch) difference between LCG and the center of rotation.

Experimental Description

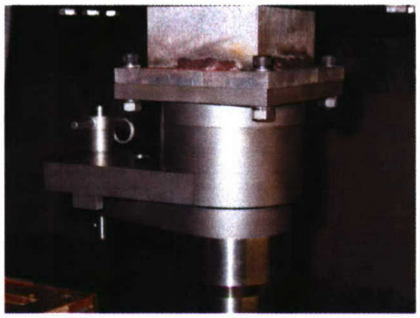
Model 5613 was fitted with a roll/pitch mechanism (Figure 3(a)) that forced the model to a maximum roll angle of 50 degrees, while allowing the model to pitch freely to 25 degrees in both directions. The mechanism was located at the center of gravity of the model. A heave post allowed the model to move in heave, while a yaw mechanism (Figure 3(b)) permitted the model to either be fixed in yaw or free to yaw up to 15 degrees. The section of the model containing the roll/pitch mechanism was separated from the rest of the model and filled with expanding foam to minimize the amount that the section could hold. At the beginning of the test, this section was filled with water. As the model rolled over, the water inside this section was exchanged with the water outside the model, keeping the total volume the same (Figure 4). The rest of the model sections were fitted with Lexan covers to keep water out. Figure 5 shows the model with the motor and gearbox assembly inside.

Three-component force and moment measurements were made using a Kistler force gage, which was mounted to the model interior underneath the roll/pitch mechanism, as shown Figure 6. The Kistler gage was used to measure the forces and moments resulting from the constrained motions, including the sway force, the drag force, and the yaw moment for the fixed yaw configuration. The amplitudes and accelerations of the free motions (heave, pitch, and yaw for the free yaw configuration) were measured using a motion package built at NSWCCD. The motion package was mounted inside the hull 88.6 cm (34.9 inches) forward of midship and 2.5 cm (0.97 inches) above the center of gravity. Vertical acceleration is reported at this point near the bow in model coordinates. Pitch and roll motion values remain the same regardless of location. Standard frame rate (30 fps) video cameras were used to visually document ship motions from multiple views.

The conditions that were tested include fixed yaw/free to yaw, six roll amplitudes (from 5 degrees to 50 degrees, in addition to the zero roll condition) 5 roll periods



(a) Roll/Pitch mechanism



(b) Yaw mechanism

Figure 3. Experimental setup.

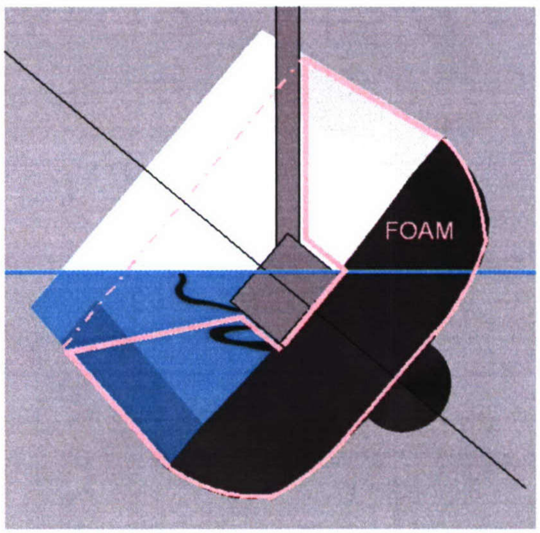


Figure 4. Model Section with Foam.

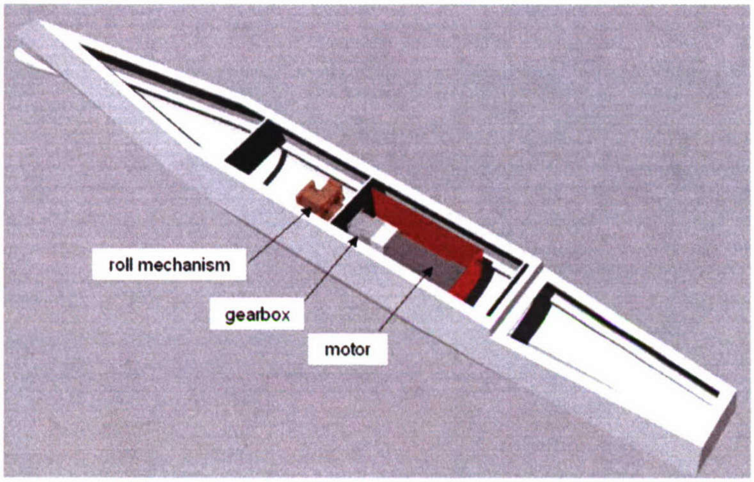


Figure 5. Model with motor and gearbox.

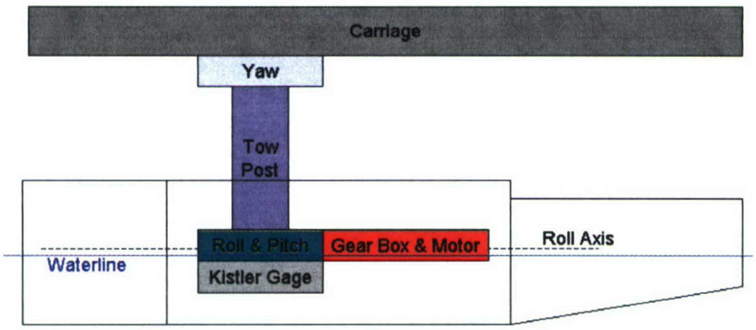


Figure 6. Schematic of model setup.

Table 2. Fixed in Yaw Test Matrix

Roll Amp. (degrees)	Roll Period (seconds)	Carriage Speed (Fn) (m/s)
0	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
5	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
10	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
20	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
30	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
45	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)
50	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7), 0.4 (2.7)

Table 3. Free to Yaw Test Matrix

Roll Amp. (degrees)	Roll Period (seconds)	Carriage Speed (Fn) (m/s)
0	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7)
5	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7)
10	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7)
20	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7)
30	1, 1.5, 2, 2.5, 3	0 (0), 0.15 (1.0), 0.25 (1.7)

(from 1 to 3 seconds), three carriage speeds (from a Froude number (Fn) of 0.15 to 0.4, plus the zero speed condition), and with and without bilge keels. At a roll angle of 30 degrees, the bilge keels were out of the water, and at 50 degrees the deck was submerged. Table 2 shows the test matrix with the conditions tested where the model was fixed in yaw. Each run was repeated three times. Table 3 shows the test matrix with the conditions tested where the model was free to yaw.

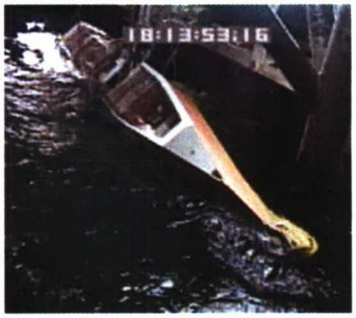
Figure 7(a) shows the model in the zero roll position with the coordinate axes used. All angles (roll, pitch, yaw) are reported relative to the ship at this starting position. All forces, moments, and accelerations are reported in ship coordinates. Figure 7(b) shows the model in the 50 degree roll position.

Motion Response Time Series Results

The figures contained in this section show the forces, moments and motions on the model moving with a Fn of 0.25 (1.7 m/s, 3.3 kts), for the case of 5 degrees of roll (top panel), 30 degrees of roll (middle panel), and 50 degrees of roll (bottom panel), all with a 2 second period.

Figure 8 shows the roll motion (black dashed line) and the sway force (red solid line) of the model. The sway force is in phase with the roll motion, and increases with roll amplitude.

(a) Model in zero roll position.



(b) Model in 50 degree roll position.

Figure 7. Model positions during testing.

Figure 9 shows the roll motion (black dashed line) and the drag force (red solid line) of the model. Drag force varies slightly with the roll motion, but stays relatively constant throughout the run. The drag force increases with roll amplitude.

Figure 10 shows the roll motion (black dashed line) and the vertical acceleration (red solid line) of the model in ship coordinates at the motion package location (88.6 cm (34.9 inches) forward of midship). At the lower roll angle of 5 degrees, there is little vertical acceleration. For the 30 degree and 50 degree cases, acceleration is -1 at the zero roll angle. Then there are two positive peaks in the heave signal in one roll period; one for maximum roll to port, one for maximum roll to starboard. These peaks exist because as the ship rolls to one side, there is more volume submerged, which creates a larger buoyant force, causing the ship to move vertically.

Figure 11 shows the roll motion (black dashed line) and the pitch motion (red solid line) of the model. In this coordinate system, pitch angle is negative when the bow is up. The pitch angle remains small, even for the largest roll amplitude. It appears that the model settles into a trim angle and stays fairly steady, with some small motion variation with respect to roll. The magnitude of the pitch angle does increase with increased roll angle.

Figure 12 shows the roll motion (black dashed line) and the yaw moment (red solid line) of the model at the center of rotation. Roll motion and yaw moment are out of phase, and the amplitude of the yaw moment increases with increased roll motion.

The data collected during this experiment were analyzed using a zero-crossing method to obtain the peak forces and moments. Repeated runs were averaged together to get one value for each case to examine trends between roll angle, roll period, speed, forces and moments. Again, all angles (roll, pitch, yaw) are reported relative to the ship at the starting zero roll position. All forces, moments, and accelerations are reported in ship coordinates. Figure 7(a) shows the model in the zero roll position with the coordinate axes used. Tables 4 through 15 below show the maximum and average forces, moments, and accelerations measured during testing. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved. Zero degree cases are not shown for the sway and yaw cases because there is side force when

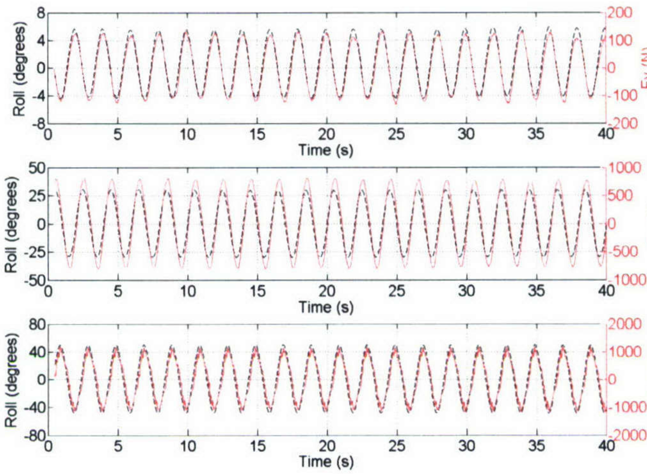


Figure 8. Sway force on model for 5 degree roll (top panel), 30 degree roll (middle panel), and 50 degree roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts).

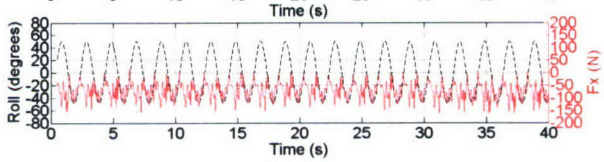


Figure 9. Drag force on model for 5 degree roll (top panel), 30 degree roll (middle panel), and 50 degree roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts).

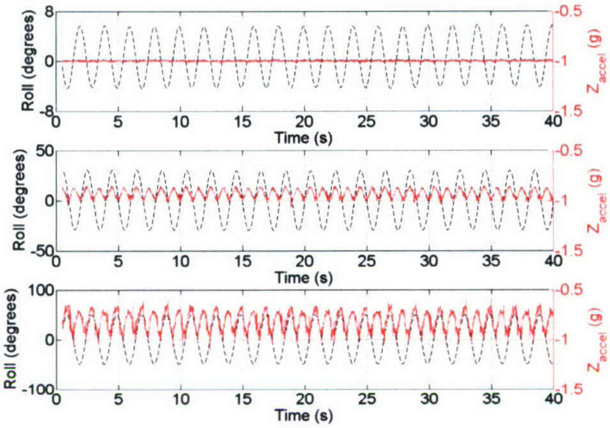


Figure 10. Vertical acceleration of model for 5 degree roll (top panel), 30 degree roll (middle panel), and 50 degree roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts).

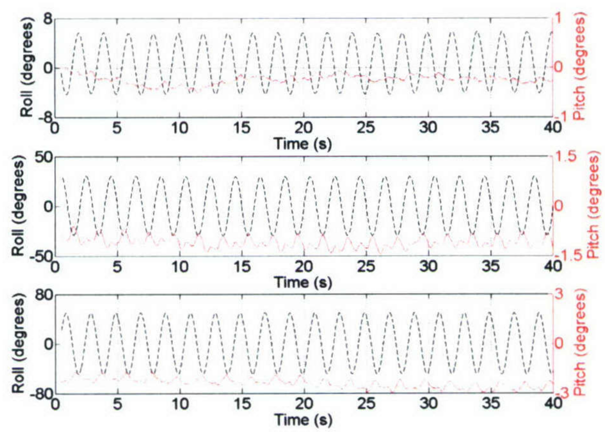


Figure 11. Pitch motion of model for 5 degree roll (top panel), 30 degree roll (middle panel), and 50 degree roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts). (In this coordinate system, a negative angle indicates that the bow is up).

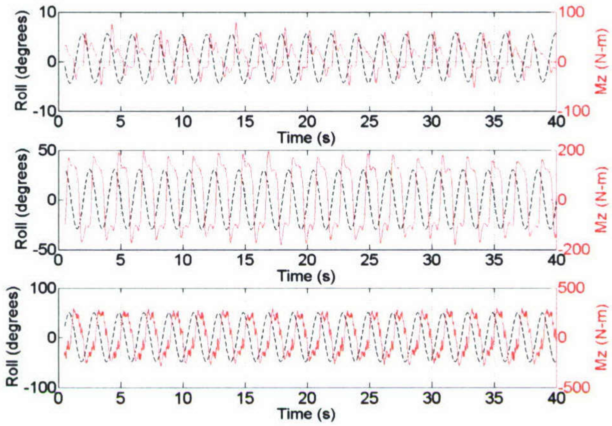


Figure 12. Yaw moment of model for 5 degree roll (top panel), 30 degree roll (middle panel), and 50 degree roll (bottom panel) for a 2 second roll period at Fn of 0.25 (1.7 m/s, 3.3 kts).

the model is not rolling.

Table 4 and Table 5 show the average maximum sway forces for the runs with and without bilge keels for the fixed in yaw conditions. Table 6 and Table 7 show the average drag forces for the runs with and without bilge keels for the fixed in yaw conditions.

Table 8 and Table 9 show the average maximum vertical accelerations over all runs with and without bilge keels for the fixed in yaw conditions of the model at the motion package location (88.6 cm (34.9 inches) forward of midship) in the model coordinate system. Table 10 and Table 11 show the average trim over all runs with and without bilge keels for the fixed in yaw conditions.

Table 12 and Table 13 show the average maximum yaw moment about the center of rotation over all runs with and without bilge keels for the fixed in yaw conditions. Because the LCG of the model is slightly different than the center of rotation, the yaw moment is corrected to show the moment about LCG. These corrected yaw moments (to the center of gravity) are shown in Table 14 and Table 15.

Table 4. Average Maximum Sway Forces (N) with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved. Zero degree cases are not shown because there is no side force for these cases.

Speed	5	10	20	30	45	50	Period
0.0	241.7	470.4	823.3	1083.0	1045.5	1155.2	**1.0**
2.0	201.6	366.6	698.5	974.2	1098.0	1002.4	**1.0**
3.3	179.2	374.9	697.5	1008.6	1133.3	N/A	**1.0**
5.3	203.8	370.7	715.0	978.8	1207.8	N/A	**1.0**
0.0	130.0	277.2	550.3	767.7	930.3	968.7	**1.5**
2.0	143.4	279.5	583.1	813.4	1013.5	1072.1	**1.5**
3.3	180.0	290.7	565.9	798.4	960.3	983.5	**1.5**
5.3	133.9	265.7	550.4	821.4	1055.7	1084.3	**1.5**
0.0	101.0	223.7	480.2	688.2	922.1	968.9	**2.0**
2.0	111.9	229.8	489.7	705.0	933.2	993.8	**2.0**
3.3	118.8	225.6	492.3	707.8	903.3	932.9	**2.0**
5.3	119.7	211.3	486.4	748.0	1000.4	1028.9	**2.0**
0.0	105.3	217.2	450.0	641.8	893.2	966.8	**2.5**
2.0	106.3	214.8	439.7	633.0	885.2	954.3	**2.5**
3.3	106.6	217.3	446.5	639.5	853.1	918.0	**2.5**
5.3	109.0	220.6	456.4	697.8	974.8	1027.7	**2.5**
0.0	101.4	208.2	437.5	632.2	891.0	966.5	**3.0**
2.0	101.3	206.3	426.3	606.0	837.5	904.5	**3.0**
3.3	100.4	207.1	431.7	623.2	838.6	897.0	**3.0**
5.3	105.3	217.5	451.9	691.5	951.2	1004.7	**3.0**

Conclusions

This experiment has generated a range of forces and moments experienced by a surface combatant hull due to large amplitude motions. The equipment is now in place to test other roll angles and periods, or possibly other hull types in future experiments. Future planned testing includes similar roll motion conditions of the same hull in head seas.

This experiment has provided an extensive database of forces and moments from roll amplitudes extending up through 50 degrees, which will be useful in verifying that model predictions are accurate in the upper range of roll amplitudes.

Table 5. Average Maximum Sway Forces (N) without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved. Zero degree cases are not shown because there is no side force for these cases.

Speed	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	161.1	293.6	777.3	1022.5	1142.4	N/A	**1.0**
2.0	134.4	246.9	577.8	853.8	1048.8	N/A	**1.0**
3.3	135.1	248.7	586.7	858.1	1009.6	N/A	**1.0**
5.3	138.4	248.6	595.4	880.3	1127.3	N/A	**1.0**
0.0	109.2	229.5	368.2	626.9	893.2	992.9	**1.5**
2.0	105.5	232.5	522.7	749.1	1008.1	1046.6	**1.5**
3.3	101.3	219.5	525.9	735.2	937.8	994.2	**1.5**
5.3	100.5	210.6	495.8	763.4	985.6	1030.2	**1.5**
0.0	93.7	194.6	417.3	594.7	851.7	950.9	**2.0**
2.0	97.3	199.0	446.5	650.2	890.4	972.9	**2.0**
3.3	95.2	197.8	450.2	653.2	867.4	926.2	**2.0**
5.3	103.0	206.7	437.4	691.6	927.9	964.0	**2.0**
0.0	93.0	183.8	396.2	578.2	839.2	915.5	**2.5**
2.0	97.2	193.1	410.9	587.7	827.4	890.9	**2.5**
3.3	95.3	199.8	424.4	603.5	809.9	872.9	**2.5**
5.3	103.9	203.3	436.5	662.7	902.1	947.0	**2.5**
0.0	89.0	178.4	388.9	580.5	810.8	884.8	**3.0**
2.0	89.4	184.8	403.9	577.2	803.3	862.5	**3.0**
3.3	89.0	194.7	418.5	594.1	796.7	850.5	**3.0**
5.3	96.5	204.0	435.2	649.4	887.1	922.4	**3.0**

Table 6. Average Drag Forces (N) with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	0	5	10	20	30	45	50	Period
0.0	0.0	-8.0	-1.1	-10.9	-15.4	-16.7	-11.4	**1.0**
2.0	-9.6	-15.0	-13.5	-18.8	-28.2	-35.3	-19.8	**1.0**
3.3	-28.0	-32.1	-33.6	-34.6	-46.4	-52.4	N/A	**1.0**
5.3	-90.8	-94.0	-96.2	-102.5	-97.3	-91.5	N/A	**1.0**
0.0	0.0	0.0	-11.5	-33.1	-56.3	-55.9	-55.8	**1.5**
2.0	-9.6	-10.7	-14.0	-30.4	-45.1	-67.8	-79.6	**1.5**
3.3	-28.0	-29.4	-31.7	-38.6	-63.2	-112.3	-103.3	**1.5**
5.3	-90.8	-91.1	-93.6	-106.8	-119.9	-134.0	-147.0	**1.5**
0.0	0.0	0.2	-0.2	-1.9	0.3	-25.2	-28.6	**2.0**
2.0	-9.6	-10.7	-12.1	-16.7	-15.4	-27.0	-42.8	**2.0**
3.3	-28.0	-29.1	-30.6	-37.3	-38.5	-65.7	-71.1	**2.0**
5.3	-90.8	-92.6	-94.2	-100.1	-103.4	-124.2	-139.0	**2.0**
0.0	0.0	0.0	-0.2	-0.9	0.4	0.5	-11.2	**2.5**
2.0	-9.6	-10.2	-11.1	-13.8	-14.1	-17.9	-25.8	**2.5**
3.3	-28.0	-28.0	-29.8	-33.7	-36.5	-50.0	-66.4	**2.5**
5.3	-90.8	-91.1	-87.9	-97.1	-101.6	-117.8	-134.1	**2.5**
0.0	0.0	-0.1	-0.2	-0.7	0.2	1.2	-0.4	**3.0**
2.0	-9.6	-10.1	-10.8	-12.9	-12.6	-14.0	-18.0	**3.0**
3.3	-28.0	-28.2	-29.4	-32.8	-34.6	-43.7	-54.8	**3.0**
5.3	-90.8	-91.6	-92.7	-96.1	-100.3	-113.6	-125.1	**3.0**

Table 7. Average Drag Forces (N) without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**0**	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	0.0	0.3	-0.3	-4.1	-7.3	-16.0	N/A	**1.0**
2.0	-9.3	-9.8	-10.9	-11.8	-15.9	-27.7	N/A	**1.0**
3.3	-26.5	-27.1	-29.0	-25.1	-31.8	-44.6	N/A	**1.0**
5.3	-87.9	-87.3	-89.6	-83.5	-76.5	-84.1	N/A	**1.0**
0.0	0.0	1.0	3.0	6.5	6.5	2.0	-0.2	**1.5**
2.0	-9.3	-8.7	-7.4	-8.3	-3.3	-17.4	-22.7	**1.5**
3.3	-26.5	-26.4	-24.6	-30.3	-22.3	-41.4	-51.0	**1.5**
5.3	-87.9	-87.8	-84.5	-90.1	-84.2	-93.8	-109.9	**1.5**
0.0	0.0	3.2	2.3	1.1	-1.0	5.3	2.4	**2.0**
2.0	-9.3	-6.2	-8.0	-11.7	-15.1	-16.1	-20.8	**2.0**
3.3	-26.5	-23.7	-25.6	-29.8	-35.3	-41.7	-48.6	**2.0**
5.3	-87.9	-85.3	-87.5	-91.6	-99.2	-105.1	-113.4	**2.0**
0.0	0.0	-0.3	-0.5	-1.9	-0.6	2.3	1.1	**2.5**
2.0	-9.3	-9.5	-10.7	-13.5	-13.6	-14.6	-19.4	**2.5**
3.3	-26.5	-27.0	-28.3	-31.7	-33.5	-41.9	-50.7	**2.5**
5.3	-87.9	-89.8	-90.7	-93.4	-96.1	-108.5	-116.8	**2.5**
0.0	0.0	1.9	0.6	4.2	-1.1	-1.4	1.5	**3.0**
2.0	-9.3	-6.8	-13.0	-6.7	-12.5	-15.2	-14.4	**3.0**
3.3	-26.5	-24.0	-26.0	-24.2	-31.6	-42.1	-45.6	**3.0**
5.3	-87.9	-86.6	-88.4	-86.8	-94.2	-109.5	-115.3	**3.0**

Table 8. Average Maximum Vertical Accelerations (g) with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**0**	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	-1.00	-0.99	-0.98	-0.94	-0.88	-0.75	-0.72	**1.0**
2.0	-1.00	-0.99	-0.99	-0.96	-0.90	-0.77	-0.61	**1.0**
3.3	-1.00	-0.99	-0.99	-0.96	-0.91	-0.78	N/A	**1.0**
5.3	-1.00	-0.99	-0.99	-0.96	-0.91	-0.79	N/A	**1.0**
0.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.81	-0.78	**1.5**
2.0	-1.00	-1.00	-0.99	-0.97	-0.92	-0.82	-0.78	**1.5**
3.3	-1.00	-1.00	-0.99	-0.96	-0.92	-0.82	-0.78	**1.5**
5.3	-1.00	-1.00	-0.99	-0.96	-0.92	-0.82	-0.78	**1.5**
0.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.82	-0.77	**2.0**
2.0	-1.00	-0.99	-0.99	-0.96	-0.91	-0.81	-0.77	**2.0**
3.3	-1.00	-0.99	-0.99	-0.95	-0.91	-0.80	-0.76	**2.0**
5.3	-1.00	-1.00	-0.99	-0.96	-0.91	-0.80	-0.75	**2.0**
0.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.79	-0.73	**2.5**
2.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.79	-0.73	**2.5**
3.3	-1.00	-1.00	-0.99	-0.96	-0.91	-0.79	-0.73	**2.5**
5.3	-1.00	-1.00	-0.99	-0.95	-0.90	-0.79	-0.73	**2.5**
0.0	-1.00	-1.00	-0.99	-0.95	-0.89	-0.77	-0.72	**3.0**
2.0	-1.00	-1.00	-0.99	-0.95	-0.89	-0.77	-0.72	**3.0**
3.3	-1.00	-1.00	-0.99	-0.95	-0.90	-0.77	-0.72	**3.0**
5.3	-1.00	-1.00	-0.99	-0.95	-0.89	-0.77	-0.72	**3.0**

Table 9. Average Maximum Vertical Accelerations (g) without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	0	5	10	20	30	45	50	Period
0.0	-1.00	-0.99	-0.98	-0.95	-0.91	-0.78	N/A	**1.0**
2.0	-1.00	-0.99	-0.99	-0.95	-0.91	-0.80	N/A	**1.0**
3.3	-1.00	-0.99	-0.99	-0.96	-0.91	-0.80	N/A	**1.0**
5.3	-1.00	-0.99	-0.62	-0.95	-0.91	-0.80	N/A	**1.0**
0.0	-1.00	-1.00	-0.99	-0.96	-0.92	-0.82	-0.78	**1.5**
2.0	-1.00	-1.00	-0.99	-0.96	-0.92	-0.80	-0.77	**1.5**
3.3	-1.00	-1.00	-0.99	-0.96	-0.91	-0.80	-0.75	**1.5**
5.3	-1.00	-1.00	-0.99	-0.96	-0.91	-0.81	-0.75	**1.5**
0.0	-1.00	-1.00	-0.99	-0.95	-0.92	-0.80	-0.75	**2.0**
2.0	-1.00	-1.00	-0.99	-0.96	-0.92	-0.79	-0.75	**2.0**
3.3	-1.00	-1.00	-0.99	-0.95	-0.91	-0.79	-0.74	**2.0**
5.3	-1.00	-1.00	-0.99	-0.95	-0.92	-0.79	-0.74	**2.0**
0.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.79	-0.73	**2.5**
2.0	-1.00	-1.00	-0.99	-0.96	-0.91	-0.78	-0.73	**2.5**
3.3	-1.00	-1.00	-0.99	-0.96	-0.91	-0.79	-0.73	**2.5**
5.3	-1.00	-1.00	-0.99	-0.95	-0.90	-0.78	-0.72	**2.5**
0.0	-1.00	-1.00	-0.99	-0.95	-0.90	-0.77	-0.72	**3.0**
2.0	-1.00	-1.00	-0.49	-0.95	-0.90	-0.77	-0.72	**3.0**
3.3	-1.00	-1.00	-0.99	-0.95	-0.90	-0.77	-0.72	**3.0**
5.3	-1.00	-1.00	-0.99	-0.95	-0.89	-0.77	-0.72	**3.0**

Table 10. Average Trim (degrees) with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**0**	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	-0.2	-0.3	-0.3	-1.0	-2.5	-5.6	-6.2	**1.0**
2.0	-0.3	-0.3	-0.3	-1.1	-2.4	-5.3	-5.8	**1.0**
3.3	-0.4	-0.3	-0.4	-1.0	-2.3	-5.7	NaN	**1.0**
5.3	-0.2	-0.2	-0.2	-0.7	-2.0	-5.2	NaN	**1.0**
0.0	-0.2	-0.2	-0.4	-0.7	-1.2	-2.6	-2.8	**1.5**
2.0	-0.3	-0.3	-0.3	-0.7	-1.3	-2.5	-2.9	**1.5**
3.3	-0.4	-0.4	-0.3	-0.7	-1.3	-2.6	-3.2	**1.5**
5.3	-0.2	-0.1	-0.3	-0.7	-1.3	-2.6	-3.2	**1.5**
0.0	-0.2	-0.2	-0.3	-0.5	-0.9	-1.7	-2.0	**2.0**
2.0	-0.3	-0.3	-0.2	-0.5	-0.8	-1.8	-2.1	**2.0**
3.3	-0.4	-0.2	-0.2	-0.5	-0.9	-2.0	-2.3	**2.0**
5.3	-0.2	-0.2	-0.2	-0.4	-0.9	-1.8	-2.3	**2.0**
0.0	-0.2	-0.3	-0.3	-0.5	-0.8	-1.5	-1.8	**2.5**
2.0	-0.3	-0.3	-0.3	-0.5	-0.9	-1.6	-1.9	**2.5**
3.3	-0.4	-0.4	-0.3	-0.6	-0.9	-1.7	-2.0	**2.5**
5.3	-0.2	-0.2	-0.3	-0.4	-0.8	-1.6	-1.9	**2.5**
0.0	-0.2	-0.2	-0.3	-0.5	-0.8	-1.5	-1.7	**3.0**
2.0	-0.3	-0.3	-0.3	-0.5	-0.9	-1.5	-1.8	**3.0**
3.3	-0.4	-0.3	-0.4	-0.5	-0.9	-1.6	-1.9	**3.0**
5.3	-0.2	-0.2	-0.2	-0.4	-0.7	-1.4	-1.6	**3.0**

Table 11. Average Trim (degrees) without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**0**	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	-0.2	-0.3	-0.6	-0.9	-1.6	-3.0	NaN	**1.0**
2.0	-0.1	-0.3	-0.6	-1.0	-1.8	-3.4	NaN	**1.0**
3.3	-0.2	-0.4	-0.6	-1.0	-1.7	-3.6	NaN	**1.0**
5.3	0.0	-0.2	-0.5	-1.1	-1.9	-4.5	NaN	**1.0**
0.0	-0.2	0.0	-0.4	-0.9	-1.2	-1.8	-2.0	**1.5**
2.0	-0.1	-0.1	-0.4	-0.8	-1.3	-2.5	-3.0	**1.5**
3.3	-0.2	-0.1	-0.5	-0.7	-1.3	-2.9	-3.3	**1.5**
5.3	0.0	0.1	-0.3	-0.7	-1.3	-2.3	-3.0	**1.5**
0.0	-0.2	-0.1	-0.1	-0.3	-0.9	-1.6	-1.8	**2.0**
2.0	-0.1	-0.2	-0.2	-0.4	-0.9	-1.6	-2.0	**2.0**
3.3	-0.2	-0.2	-0.2	-0.5	-0.9	-1.6	-2.1	**2.0**
5.3	0.0	0.0	0.1	-0.3	-0.7	-1.3	-1.7	**2.0**
0.0	-0.2	-0.1	-0.2	-0.4	-0.7	-1.3	-1.5	**2.5**
2.0	-0.1	-0.1	-0.2	-0.3	-0.7	-1.3	-1.7	**2.5**
3.3	-0.2	-0.2	-0.2	-0.3	-0.7	-1.4	-1.9	**2.5**
5.3	0.0	0.0	0.0	-0.2	-0.6	-1.4	-1.5	**2.5**
0.0	-0.2	-0.2	-0.2	-0.3	-0.4	-0.8	-1.0	**3.0**
2.0	-0.1	-0.2	-0.2	-0.3	-0.5	-0.8	-0.9	**3.0**
3.3	-0.2	-0.2	-0.3	-0.4	-0.8	-1.4	-1.7	**3.0**
5.3	0.0	0.0	-0.1	-0.3	-0.6	-1.2	-1.5	**3.0**

Table 12. Average Maximum Yaw Moment (N-m) about the Center of Rotation with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	147.0	247.6	318.5	363.4	325.3	342.1	**1.0**
2.0	114.6	197.4	270.5	310.1	358.9	351.3	**1.0**
3.3	96.8	166.8	262.8	290.6	348.1	N/A	**1.0**
5.3	68.9	112.1	183.7	248.7	336.5	N/A	**1.0**
0.0	78.7	140.8	248.2	297.6	293.3	289.3	**1.5**
2.0	57.5	96.8	163.3	206.8	259.0	274.3	**1.5**
3.3	60.3	86.3	135.7	200.5	273.2	282.1	**1.5**
5.3	44.4	84.6	149.8	205.1	258.4	247.6	**1.5**
0.0	27.5	49.5	80.0	117.1	149.3	156.3	**2.0**
2.0	28.7	49.1	66.9	105.6	174.0	194.6	**2.0**
3.3	32.0	53.7	104.4	156.3	220.5	216.5	**2.0**
5.3	22.4	47.6	118.1	186.2	256.1	266.3	**2.0**
0.0	12.2	16.2	28.7	56.8	109.5	136.1	**2.5**
2.0	12.1	17.3	29.7	60.0	110.1	122.8	**2.5**
3.3	19.8	39.1	72.7	102.3	138.0	140.6	**2.5**
5.3	13.9	34.3	86.3	145.8	188.3	199.7	**2.5**
0.0	6.8	11.8	34.4	56.5	97.4	115.2	**3.0**
2.0	9.4	15.9	39.4	65.1	91.5	104.9	**3.0**
3.3	11.0	26.1	53.3	74.7	98.6	120.0	**3.0**
5.3	12.4	26.8	71.1	118.3	166.7	182.8	**3.0**

Table 13. Average Maximum Yaw Moment (N-m) about the Center of Rotation without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	95.9	198.5	327.8	344.0	318.8	N/A	**1.0**
2.0	94.5	184.9	296.7	340.3	362.4	N/A	**1.0**
3.3	78.4	158.7	286.2	331.9	356.6	N/A	**1.0**
5.3	50.5	109.5	229.8	292.3	334.8	N/A	**1.0**
0.0	100.1	136.7	222.6	303.0	320.8	329.0	**1.5**
2.0	74.3	106.4	193.0	269.8	321.5	331.3	**1.5**
3.3	61.7	89.5	177.1	258.6	314.9	325.2	**1.5**
5.3	55.0	78.3	166.7	236.3	290.1	289.4	**1.5**
0.0	32.8	55.5	85.7	118.6	158.8	162.9	**2.0**
2.0	28.8	54.7	89.1	139.7	216.8	219.7	**2.0**
3.3	27.4	53.6	105.1	168.0	251.6	250.1	**2.0**
5.3	26.4	50.3	104.6	165.8	239.3	234.5	**2.0**
0.0	15.0	21.3	31.8	52.8	104.2	130.1	**2.5**
2.0	18.8	23.3	32.3	52.1	82.5	99.9	**2.5**
3.3	21.5	38.6	65.9	96.0	136.8	140.1	**2.5**
5.3	22.9	32.0	73.0	114.1	164.6	180.3	**2.5**
0.0	6.5	9.1	35.2	57.0	96.6	116.8	**3.0**
2.0	7.0	14.8	27.4	42.7	76.1	96.1	**3.0**
3.3	7.1	19.4	42.0	55.3	71.4	85.6	**3.0**
5.3	9.7	21.4	53.4	94.8	123.5	134.9	**3.0**

Table 14. Average Maximum Yaw Moment (N-m) about the LCG with Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	153.8	260.7	341.5	393.7	354.5	374.4	**1.0**
2.0	120.2	207.6	290.0	337.3	389.6	379.3	**1.0**
3.3	101.8	177.3	282.3	318.8	379.8	N/A	**1.0**
5.3	74.6	122.4	203.7	276.0	370.2	N/A	**1.0**
0.0	82.4	148.5	263.6	319.0	319.3	316.4	**1.5**
2.0	61.5	104.7	179.6	229.5	287.3	304.2	**1.5**
3.3	65.4	94.4	151.5	222.9	300.1	309.5	**1.5**
5.3	48.1	92.0	165.2	228.0	287.9	277.9	**1.5**
0.0	30.3	55.8	93.4	136.3	175.1	183.4	**2.0**
2.0	31.8	55.6	80.6	125.3	200.1	222.4	**2.0**
3.3	35.3	60.0	118.2	176.1	245.7	242.5	**2.0**
5.3	25.7	53.5	131.7	207.1	284.0	295.0	**2.0**
0.0	15.2	22.3	41.2	74.8	134.5	163.2	**2.5**
2.0	15.0	23.3	42.0	77.7	134.8	149.5	**2.5**
3.3	22.8	45.1	85.2	120.2	161.8	166.3	**2.5**
5.3	17.0	40.5	99.1	165.3	215.5	228.4	**2.5**
0.0	9.6	17.6	46.7	74.2	122.3	142.2	**3.0**
2.0	12.2	21.6	51.3	82.0	114.9	130.1	**3.0**
3.3	13.8	31.8	65.4	92.1	122.0	145.1	**3.0**
5.3	15.3	32.9	83.7	137.6	193.2	210.8	**3.0**

Table 15. Average Maximum Yaw Moment (N-m) about the LCG without Bilge Keels, Fixed in Yaw. Runs for the shortest periods at the 50 degree angle were not made due to the large forces involved.

Speed	**5**	**10**	**20**	**30**	**45**	**50**	**Period**
0.0	100.4	206.7	349.5	372.5	350.7	N/A	**1.0**
2.0	98.3	191.8	312.9	364.1	391.7	N/A	**1.0**
3.3	82.2	165.6	302.6	355.9	384.9	N/A	**1.0**
5.3	54.3	116.4	246.4	316.9	366.3	N/A	**1.0**
0.0	103.1	143.1	232.9	320.5	345.7	356.7	**1.5**
2.0	77.2	112.9	207.6	290.7	349.6	360.6	**1.5**
3.3	64.6	95.6	191.8	279.2	341.1	353.0	**1.5**
5.3	57.8	84.2	180.6	257.6	317.6	318.2	**1.5**
0.0	35.5	61.0	97.4	135.2	182.6	189.4	**2.0**
2.0	31.5	60.2	101.5	157.9	241.7	246.9	**2.0**
3.3	30.0	59.1	117.6	186.2	275.8	275.9	**2.0**
5.3	29.2	56.1	116.8	185.1	265.3	261.4	**2.0**
0.0	17.6	26.4	42.9	69.0	127.6	155.6	**2.5**
2.0	21.5	28.7	43.7	68.6	105.7	124.8	**2.5**
3.3	24.1	44.2	77.7	112.9	159.4	164.4	**2.5**
5.3	25.8	37.7	85.2	132.6	189.8	206.7	**2.5**
0.0	9.0	14.1	46.1	73.2	119.2	141.5	**3.0**
2.0	9.5	19.9	38.7	58.8	98.6	120.2	**3.0**
3.3	9.6	24.8	53.7	71.9	93.6	109.4	**3.0**
5.3	12.4	27.1	65.6	112.9	148.3	160.7	**3.0**

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